NASA's Watts on The Moon Challenge
Competition Level 3 Technical Guidance
November 30, 2023

This document is intended to help teams prepare for the final competition and testing in Level 3. This document replaces Appendix G: Preliminary Testing Operations in Competition Level 3 in the Challenge Rules. Please do not refer to Appendix G for guidance in Level 3.

This document was initially released in draft form on August 3, 2023; an updated version was released on September 29, 2023. This November 30 version includes the following updates, highlighted in gray in the document:

- Updated size specifications for the cold wall and updated FIGURE B (pp. 2-3)
- Minor reduction in the initial hours of the load profile, to address a safety issue (pp. 4-5)
- Updated FIGURE 1 from the challenge rules, showing the minor reduction in the initial hours of the load profile (p. 5)
- Updated guidance on ground connections (p. 7)

Questions regarding these updates or any other details in this document can be submitted to jamie@herox.com or through the challenge website.

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1. Facility Details

Updated Testing Configuration

The expected testing configuration is illustrated in FIGURES A–D below. These FIGURES replace FIGURE 2 in the Challenge Rules.

FIGURE A shows Vacuum Facility 3 (VF-3) at the NASA Glenn Research Center, which is where the Level 3 testing will take place.

FIGURE B shows an end view of VF-3. The diagram shows an inner diameter from the LN2 cold wall of 117 cm. A floor will be installed at the location shown which will provide approximately 105.4 cm (41.5 inches) of horizontal surface, with a maximum height of approximately 89 cm (35 inches) at the middle and a height of approximately 68.5 cm (27 inches) at the edge of the floor. The floor is expected to run the length of the chamber, which is about 3.7 m (144 inches). Although VF-3 is longer than the cold wall, all hardware will be located within the cold wall length. The team's hardware delivered for Level 3 testing must fit in this floor area and volume. Please note that these measurements may change slightly once the cold wall design is complete.

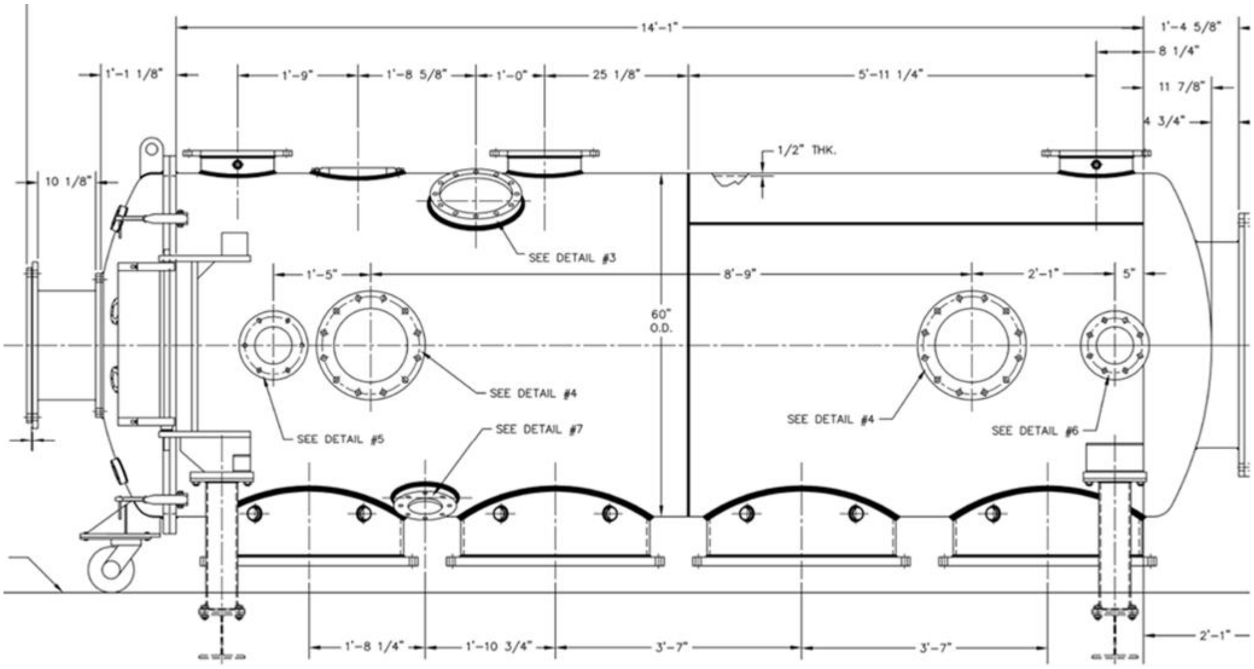
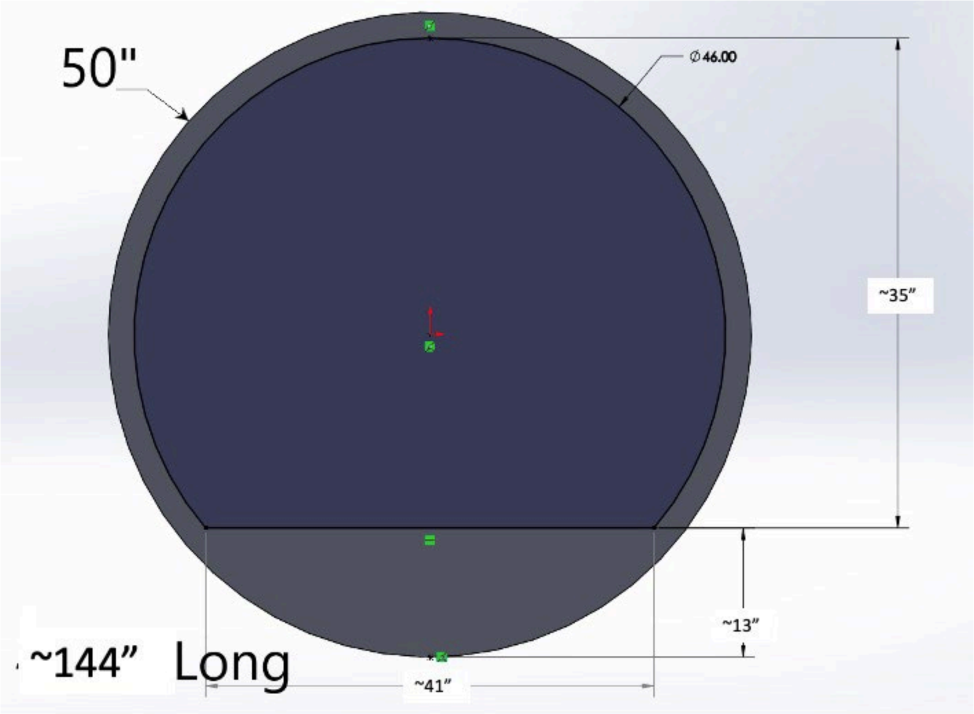


FIGURE A – Vacuum Facility 3 (VF-3)



UPDATED FIGURE B – End view of VF-3
(Note: Inside chamber is 173" long, with a cold wall length of approximately 144")

The floor/platform on which a team's hardware will be placed will be mounted on rails. The chamber floor will consist of an aluminum ladder-type frame with an electrical and thermal insulator material acting as a floor for the hardware and transmission cables. This floor will be TBD material (e.g., Teflon, FR-4, phenolic) attempting to simulate the low thermal conductivity of the lunar surface regolith. A team's hardware will not be permitted to physically contact anything other than the insulated chamber floor (except for electrical connections). For integration, the floor will be pulled out of the chamber, and the team's hardware will be integrated in the manner shown in FIGURE C below, with the transmission and receiving hardware at the door-end of the chamber and the transmission cable located on the remainder of the available floor area.

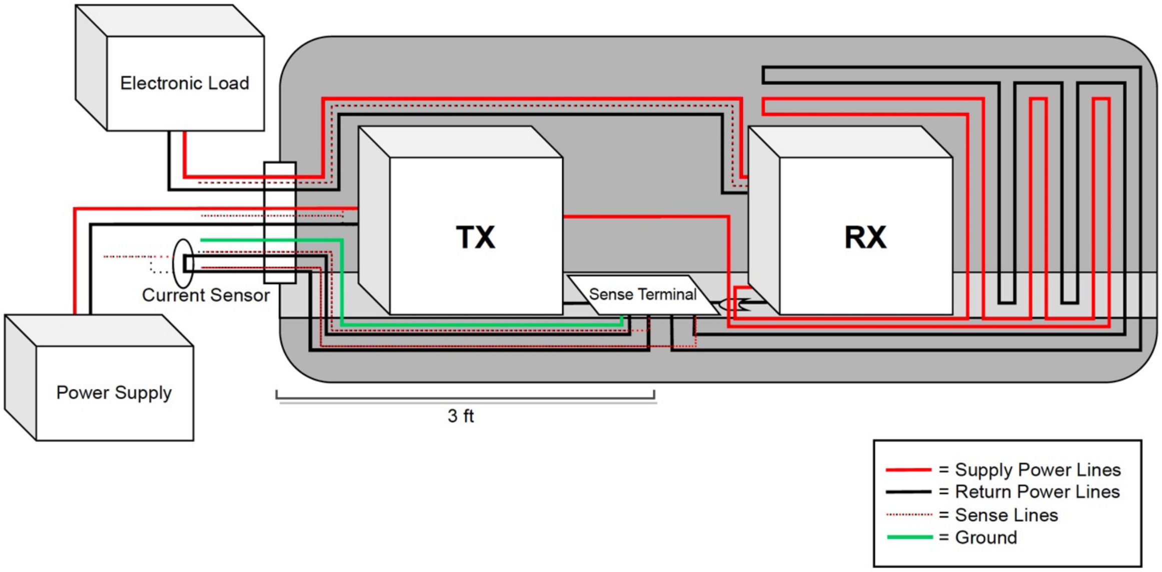


FIGURE C – Test integration concept and top-level wiring schematic (not to scale)

Properties of the LN2 Cold Walls in the Test Chamber

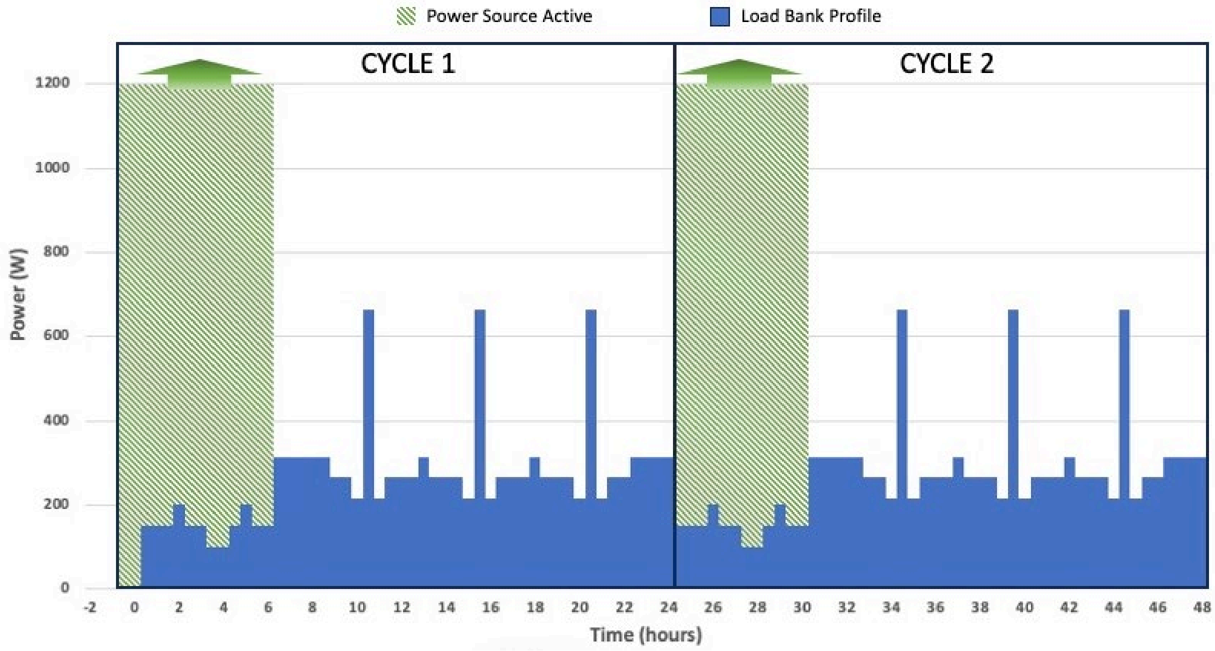
The thermal vacuum chamber will provide a nominally uniform cryogenic temperature environment in the form of a liquid nitrogen cold wall and a 10^{-3} Torr or lower vacuum. The cold wall will be flooded with LN2, and a feed valve will be controlled to ensure that no liquid LN2 escapes the cold wall vent by setting an exit temperature setpoint of around 80 K. The cold wall will be painted with a high emissivity black paint (AKZO Nobel 463-3-8) that will achieve 0.92 emissivity. The cold wall will cover the full circumference of the VF-3 wall and will be thermally insulated from the tank walls using multi-layer insulation (MLI). The ends of the cold wall will be capped with aluminum plugs at either end that are also insulated from the VF-3 chamber wall and thermally connected to the active cold wall.

Because the test facility is currently being upgraded with a new LN2 cold wall, NASA is unable to guarantee specific performance capabilities or provide performance data for the facility and the cold wall at this time. The facility and cold wall are expected to be integrated and tested in the March/April 2024 timeframe, so teams will need to make assumptions about the facility performance and account for uncertainties by using margins in their designs. Also, the cold wall design will be proprietary to the manufacturer, so specific design details and drawings will not be available to the teams. While NASA is attempting to provide a cryogenic environment, we are unable to guarantee any performance specifications teams would rely on for their designs.

After additional discussions with NASA facility and safety experts, we are modifying the initial two (2) hours for chamber conditioning. We determined that if there were high voltages present in the hardware during pump down, that could cause partial discharge, arcing, and failures of a team's hardware (see Paschen's Law). To avoid this, we will delay powering up NASA's 120Vdc power supply until after VF-3 has reached a high vacuum ($<10^{-3}$ torr). In addition, to avoid condensing water vapor on the cold wall, we will also delay the flow of LN2 until the chamber reaches high vacuum. We estimate the chamber will take approximately one (1) hour to reach a high vacuum. This delay will shorten the time that teams have to charge their energy storage systems. An updated version of FIGURE 1 – Watts on the Moon Challenge Phase 2 Load Profile reflecting this change is provided below. NASA has also updated the Phase 2 Load Profile Data spreadsheet to reflect this change, and the updated spreadsheet is available on the challenge website.

We recognize that teams may be concerned that the cold wall and the team's hardware within VF-3 may not have sufficient time to reach equilibrium temperature within a now even shorter period before the NASA load bank is switched on. However, as noted in the September 29 version of this guidance document, NASA is mostly interested in designs that can operate over a range of lunar surface temperatures, not just at very low cryogenic temperatures. Teams are reminded that the performance of the power transmission and energy storage hardware are only measured during hours 24 to 48 (Cycle 2), when temperatures are expected to be close to 77K.

Teams should note that during the first 24-hour test cycle (Cycle 1), the only criteria that must be met is that the NASA load must be provided power within the voltage range specified below, using a combination of power from the NASA 120VDC power supply and the team's energy storage system. While NASA will be measuring other performance parameters during this time, it is only during the last 24 hours of the test (Cycle 2) that NASA will record performance measurements that will be used in the Level 3 scoring. NASA expects that the tank will have reached thermal equilibrium by the beginning of this last 24-hour period (Cycle 2).



UPDATED FIGURE 1 – Watts on the Moon Challenge Phase 2 Load Profile
(This replaces FIGURE 1 from Challenge Rules)

Note: The chamber will be closed, and the pumps will be started at T-2 hours. When the tank pressure reaches approximately 10^{-3} torr, the LN2 cold wall will be filled, and the NASA power supply will be turned on. We estimate this will happen around T-1 hours. At T0, the NASA load bank will be turned on, and will follow the load schedule shown for 48 total hours. At T+6 hours, the NASA power supply will be shut off, and will turn back on again for 6 hours at T+24 hours.

2. Voltage Ranges

When the Challenge Rules were formulated, NASA used a standard voltage range for spacecraft user loads of 28VDC +/- 4VDC, resulting in guidance that teams would be required to stay within a 24–32VDC range.

However, NASA has recently adopted a new 28VDC standard for user loads as specified in the International Space Power Systems Interoperability Standard (ISPSIS). In this new standard, the load operation range has been extended to between 23–36VDC, which enables the use of lithium-ion batteries in eight-cell series (8S) configurations without additional regulation.

Therefore, we are updating the voltage range for testing operations in Level 3 to reflect this wider voltage range of 23–36VDC. The voltage delivered to the load connector on the VF-3 wall will be continuously measured by a NASA data acquisition (DAQ) system for the entire 48 hour-timeline to determine if the load voltage falls outside this voltage range.

NASA expects that teams will design their solutions to stay within this voltage range for 100% of the 48-hour timeline. As described in the Challenge Rules Appendix F, teams that successfully deliver power for 100% of the timeline (within the designated voltage range, and under the conditions described in the Challenge Rules, FIGURE 1) will receive a score equal to their Total Effective System Mass. Teams that do not successfully deliver power for 100% of the timeline will not receive a score, *unless no team successfully delivers power for 100% of the timeline*; in that case all teams will receive a score based on their Total Effective System Mass and Power Timeline Performance.

As noted in the Challenge Rules, NASA will provide a nominal 120VDC from the NASA power supply to the team's hardware. While the new International Space Power System Interface Standard (ISPSIS) does allow the 120VDC standard to range between 98–138VDC, we plan to use a regulated power supply of 120V with a 34A current limit. We will set the supply to 120VDC and will use remote voltage sense lines to regulate the 120V directly at the power input terminal block and close to the power transmission hardware inside the chamber. With this setup, we estimate that the minimum and maximum voltages should remain between 119.5–120.5VDC.

3. Transmission Cable

Minimum Distance

Teams will be required to deliver a cable that is a minimum length of 30 m. Teams may deliver a longer cable, up to 3 km; however, there is no scoring advantage to delivering a longer length of cable. If a 30 m cable is delivered, NASA technicians will install the cable on the VF-3 floor by snaking or coiling the cable (depending on bend radius) in order to maximize exposure/view factor to the LN2 cold wall. If teams deliver longer cables, the team will be responsible for ensuring that the cable can be installed with the rest of their hardware within the VF-3 area and volume limits.

Whatever length of cable is delivered, NASA will independently measure the length and mass of the cable prior to installation. Any cable delivered on a spool will be completely unspooled in order to determine the length, and the mass of the spool will be measured so it can be subtracted from the total system mass measurement.

To ensure that cable connectors are not captured in the cable mass measurement and multiplied by the fraction of missing cable, teams will be able to install any necessary connectors (e.g., a ring terminal) to their transmission cables at NASA after the mass is measured and prior to integration.

Measurement of Cable Performance During Testing

NASA is very interested in understanding the performance of the various long distance transmission technologies that will be tested in Level 3. Therefore, NASA will use instrumentation to measure the actual cable performance during the test using our own hardware and sensors. The data related to voltage drop and current collected by NASA during the last 24 hours of the test will be used to project the additional source power that would have been needed if the full 3 km distance had been measured. While we recognize that this measurement will not capture all of the other energy losses, it will capture the majority of losses and provide an excellent measure of transmission cable performance.

Although the Challenge Rules indicate that distance emulation may be used in Level 3, if a team wishes to use a distance emulator, they must still deliver at least 30 m of cable, and the emulator will need to dynamically follow the actual performance of the of cable during Level 3 testing. Even if an emulator is used, NASA will still measure the performance of the cable in order to verify that the distance emulator is dynamically tracking its performance.

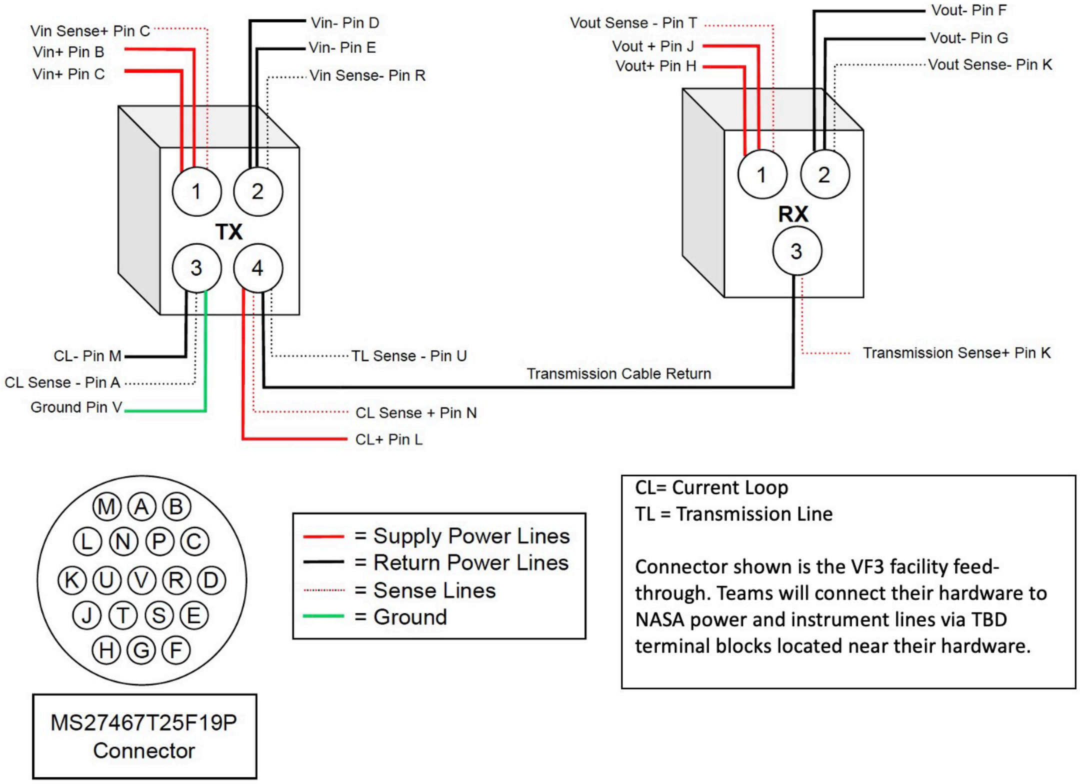
Teams will electrically integrate their transmission hardware, receiver hardware, and transmission cable using NASA-supplied terminal blocks as depicted in FIGURE D. These terminal blocks will provide electrical connections for power and instrumentation lines, as well as a NASA-supplied “loop-out” cable for measurement of the transmission line current. All voltage-drop and current measurements will take place on the transmission line “return,” and NASA will work closely with teams to ensure that all measurements are made safely and that any ground connections do not prevent operation of the team’s hardware.

The current loop-out cable will be sized for up to 5A of current and will be placed in series between the transmission hardware return connection and the transmission cable return line to eliminate any high-voltage concerns. NASA will implement the current loop-out cable in order to minimize any conducted heat leak back into the team’s hardware. The external loop will be kept as short as possible and will be insulated. This portion will pass through a closed-loop Hall effect DC current sensor with an expected resolution of < 1mA. The internal portion of the cable will be attached to the cold wall in order to maximize heat removal.

The cubic blocks shown in FIGURE D are intended to represent terminal blocks that will be used to electrically connect the team’s hardware and transmission cables together, and to the NASA-supplied power and instrumentation cables. The NASA cables will not be part of the team’s total system mass measurement. FIGURE D shows the team’s transmission cable return line and how it will be connected to the various terminals. Also shown are the 120VDC input power connections to the team’s transmission hardware (TX terminals 1 and 2) and the receiver output connections to the NASA load bank (RX terminals 1 and 2). All electrical connections will be made using a terminal block located close to the team’s hardware using ring terminals. The NASA power cables (input and load) are expected to be two (2) paralleled, stranded, Teflon-insulated 12AWG wires that will be roughly 2 m in length inside the chamber, and as short as possible outside the chamber. NASA will not be taking any special precautions to minimize conducted heat leak on these cables. Note that the MS27467T25F19P connector specified in FIGURE D is only for NASA facility use.

Lastly, not shown in the figures, NASA will provide a data connection feed into VF-3 so that teams can communicate with and monitor their hardware during testing. The default data feed-through will be an RJ-45 ethernet connection, although other data standards can be accommodated. If teams require a different data connection, they should communicate their needs to NASA prior to the safety review. For safety reasons, NASA will not allow teams to bring analog instrumentation out through the VF-3 chamber.

Teams that need or want to monitor voltages, currents, temperatures, or other data related to their hardware will need to digitize and communicate that data using a digital communications line to their own external computer. However, an external computer is only allowed to monitor hardware and turn hardware on and off. All other controls, especially energy storage management, must be included on hardware that is located inside the VF-3 chamber. Specifically, an external computer cannot be used as a means for hazard mitigation of the energy storage hardware.



CL= Current Loop
TL = Transmission Line

Connector shown is the VF3 facility feed-through. Teams will connect their hardware to NASA power and instrument lines via TBD terminal blocks located near their hardware.

FIGURE D – Proposed electrical interface schematic

4. Energy Storage Safety

NASA is particularly focused on how teams will address the hazards associated with the operation of very large energy storage systems inside a vacuum chamber. The challenge requires a minimum of 5,500Wh of energy storage, and that amount of stored energy is a significant concern.

Teams should focus on addressing the Hazard Analysis template provided by NASA, and especially the hazards that have been identified in red text as being the “Responsibility of the WOTM Teams.”

The NASA safety review will only be focused on mitigations that reduce the likelihood of a failure occurring during handling, installation, and Level 3 testing. Teams are not expected to take steps to reduce the severity of a potential energy storage system failure. However, teams will be required to “show their work” during the safety review to prove that the mitigations will be successful in reducing the likelihood of the various failure modes for their energy storage system. As noted in the Hazard Analysis template, teams must take measures to ensure safety related to their energy storage systems related to the following issues:

- Physical damage during handling
- Over-charge
- Over-temperature
- Over-discharge
- Charging at low temperatures
- External short circuits
- Manufacturing defects that can cause internal short circuits

Most energy storage systems will rely on some type of management system controller to manage these hazard risks, and teams should be prepared to prove to NASA that their controller does, in fact, effectively mitigate each of the hazards as noted in the Hazard Analysis.

5. Safety Review, Template, and Opportunity for Feedback

As noted in the Challenge Rules, teams will make a virtual presentation to a NASA safety committee up to two months before the Level 3 submission deadline. These presentations are expected to be scheduled for February 2024. The committee must approve the safety of each team’s solution before it can be delivered to any NASA facility. If NASA cannot approve a team’s solution because the solution cannot be deemed sufficiently safe, the team will be ineligible to test in a NASA facility and ineligible to win a prize.

The safety review is expected to consist of:

1) A presentation (e.g., power point) that the team will present in 30 to 60 minutes;
2) A review of a completed Hazard Analysis (using the template provided); and
3) A review of the testing that was performed to verify information included in the Hazard Analysis.

Teams are strongly encouraged to submit a draft version of their Hazard Analysis and initial supporting data and documentation by November 16, 2023. NASA will review the draft and provide feedback to teams regarding whether the information provided is sufficient or insufficient for the safety review. NASA expects to provide feedback by December 14, 2023.